Scale invariant extension of the standard model with a hidden QCD-like sector

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A scale-invariant extension of the Standard Model with a singlet-scalar and hidden-QCD sector is studied. The electroweak symmetry breaking scale is generated dynamically by an asymptotic-free hidden-QCD sector, and mediated by the Higgs-singlet coupling. Hidden-QCD pions are stable and can be a candidate of the cold dark matter. This presentation is based on the collaboration with D. W. Jung and P. Ko [1].

I. INTRODUCTION

Even after the discovery of the Higgs particle at the LHC, the origin of the electroweak scale is still an unsolved problem. Here we consider a scale-invariant extension of the Standard Model with a singlet scalar and hidden non-Abelian gauge theory[2].

The model contains the SM fields, a singlet scalar S and a scale-invariant hidden QCD sector. The Lagrangian is given by

$$\begin{aligned}\mathcal{L} \;=\; & \mathcal{L}_{\rm SM}(\mu_H^2=0) + \frac{1}{2}(\partial_\mu S)^2 - \frac{\lambda_S}{8}S^4 + \frac{\lambda_{HS}}{2}H^\dagger H S^2 \\ & -\frac{1}{2}\mathrm{tr}\, G_{\mu\nu}G^{\mu\nu} + \sum_{k=1}^{N_{h,f}} \bar{Q}_k(i\gamma^\mu D_\mu - \lambda_{Q,k}S)Q_k, \end{aligned} \tag{1}$$

where μ_H is the mass parameter of the SM Higgs. $G_{\mu\nu}$ is the field strength of the hidden-QCD with $SU(N_{h,c})$ gauge symmetry. The SM singlet scalar S couples to the hidden-QCD quarks Q_f through the Yukawa interaction λ_Q. Since there are no dimension-full parameters in the Lagrangian, this system is scale-invariant at a classical level. Thanks to the asymptotic-free behavior of the hidden-QCD, at a quantum level and at a low-energy scale, the hidden-QCD quarks can condensate $\langle \bar{Q}Q\rangle$, which induce a linear term of S. Then the potential of S can be tilted and S can develop a vacuum expectation value (VEV). The VEV of the singlet scalar generates a Higgs mass term $-\frac{\lambda_{HS}}{2}\langle S\rangle^2 H^\dagger H$. We assume that $\lambda_{HS}>0$ so that non-zero $\langle S\rangle$ triggers the electroweak symmetry breaking.

II. LINEAR SIGMA MODEL

Hereafter we consider the case in which $N_{h,c}=3$, $N_{h,f}=2$ and $\lambda_Q = \mathrm{diag}(\lambda_{Qu},\lambda_{Qd})$, $\lambda_{Qu}\sim\lambda_{Qd}$. Then the low-energy effective theory of the hidden-QCD is described by the pi-meson triplets and the sigma meson. It can be written in the form of a linear-sigma model

$$\mathcal{L}_{L\sigma M} \;=\; \frac{1}{2}(\partial_\mu\Sigma)^2 + \frac{1}{2}(\partial_\mu\pi)^2 - \frac{\lambda_\sigma}{4}(\Sigma^2+\pi^2)^2 + \frac{\mu_\sigma^2}{2}(\Sigma^2+\pi^2) + m_{S\sigma}^2 S\Sigma, \tag{2}$$

where Σ and π represents sigma and pi meson fields, respectively. We parameterize the vacuum expectation values and fluctuations of scalars as

$$H = \big(0,\ v_H + h\big)^T/\sqrt{2}, \quad S = v_S + s, \quad \Sigma = v_\sigma + \sigma. \tag{3}$$

Three vacuum conditions reduce the number of free parameters. Furthermore, two parameters λ_σ, μ_σ are traded with the pion mass M_π and a sigma meson mass parameter $M_{\sigma\sigma}$. Hence the scalar mass matrix $\mathcal{L} \supset -\frac{1}{2}(h,s,\sigma)\mathcal{M}(h,s,\sigma)^T$ takes the form of

$$\mathcal{M} \;=\; \begin{pmatrix} M_{hh}^2 & M_{hs}^2 & 0 \\ M_{hs}^2 & M_{ss}^2 & -m_{S\sigma}^2 \\ 0 & -m_{S\sigma}^2 & M_{\sigma\sigma}^2 \end{pmatrix}, \tag{4}$$

with

$$M_{hh}^2 = \lambda_H v_H^2 = \lambda_{HS} v_H^2 \tan^2\beta, \qquad M_{hs}^2 = -\lambda_{HS} v_H^2 \tan\beta, \qquad M_{ss}^2 = \lambda_{HS} v_H^2 \left(1 + \frac{3M_\pi^2 F_\pi^2}{\lambda_{HS}\tan^2\beta\, v_H^4}\right), \tag{5}$$

$$-m_{S\sigma}^2 = -\frac{M_\pi^2 F_\pi}{v_S}, \tag{6}$$

where $\tan\beta \equiv v_S/v_H$, $v_H = 246\text{GeV}$ and $F_\pi \equiv v_\sigma$. Since one of the physical scalar should be the Higgs boson with mass $m_H^2 = (125\text{GeV})^2$ is one of the eigenvalues of $\mathcal{M}$, one can use a condition $\det(\mathcal{M} - m_H^2 I_3) = 0$ (I_3 is a 3×3 unit matrix) to express λ_{HS} in an analytical form. We parameterize $M_{\sigma\sigma} = \xi_\sigma F_\pi$.

At this stage we have four free parameters: v_S, $v_\sigma \equiv F_\pi$, M_π and $M_{\sigma\sigma}$ (or ξ_σ). To reduce the number of free parameters, in particlar, to relate the $M_{\sigma\sigma}$ with F_π, we use a holographic treatment of the QCD. We follow mainly [3, 4], but unlike the original work by Rold and Pomarol[4] in which the lightest scalar meson resonance is identified with $a_0(980)$, we regard the lightest scalar meson state as the sigma meson. and we imposed a new condition for sigma-singlet mixing

$$m_{S\sigma}^2 = F_\sigma M_\sigma \tag{7}$$

where F_σ and M_σ are the decay constant and mass of the sigma meson,respectively. Using (6) and Gell-Mann–Oaks-Renner relation the above relation is written by

$$F_\sigma M_\sigma = B_0 F_\pi, \quad B_0 \equiv \langle \bar{Q}Q\rangle / F_\pi^2, \tag{8}$$

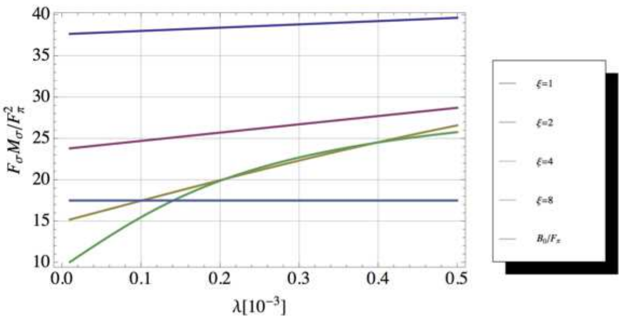

FIG. 1: Value of $F_\sigma M_\sigma$ for $\sigma = S^{(1)}$ in the AdS/QCD[4] in the unit of F_π^2.

For $\xi = 4$ we obtain for $\lambda \simeq 1.0\times 10^{-4}$. We also find that with this value we obtain $M_\sigma \simeq 5F_\pi$ ($\xi_\sigma \simeq 5$). This value well agree with the observed $f_0(500)$ meson mass $m_{f_0(500)} = 400 - 550\text{MeV}$ [5] (Fig. 2).

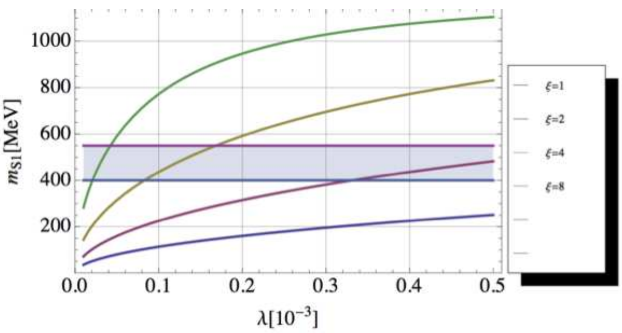

FIG. 2: Mass of the lightest scalar meson calculated in AdS/QCD framework[4]. We regard this scalar as sigma meson. Gray band indicates the allowed mass range of $f_0(500)$. We also plot $B_0 F_\pi = 17.5F_\pi^2$ as the horizontal solid line.

III. NUMERICAL ANALYSIS (PRELIMINARY)

In this preliminary study, we fix $F_\pi = 1000$GeV and consider a parameter region 50GeV $\leq M_\pi \leq 300$ and $0 \leq \tan\beta \leq 16$.

Three scalar particles (h, s, σ) is mixed with each other by the mass matrix (4). Mass-eigenstates are h', h_1, σ:

$$\begin{pmatrix} h \\ s \\ \sigma \end{pmatrix} = \begin{pmatrix} \rho_{hh'} & \rho_{hh_1} & \rho_{h\sigma'} \\ \rho_{sh'} & \rho_{sh_1} & \rho_{s\sigma'} \\ \rho_{\sigma h'} & \rho_{\sigma h_1} & \rho_{\sigma\sigma'} \end{pmatrix} \begin{pmatrix} h' \\ h_1 \\ \sigma' \end{pmatrix}, \tag{9}$$

where h' corresponds to the physical Higgs boson and $m_{h'} = 125$GeV. $m_{\sigma'} \sim M_{\sigma\sigma} \simeq 5F_\pi$. h_1 can be heavier or lighter than the physical Higgs h'. The signal strength of the Higgs production and decay will be suppressed by a mixing matrix element $\rho_{hh'}$:

$$\frac{\mu_{\rm SIM}(\bar{p}p \to h \to \bar{f}f)}{\mu_{\rm SM}(\bar{p}p \to h \to \bar{f}f)} \simeq |\rho_{hh'}|^2. \tag{10}$$

For the signal strength of our scale invariant model $\mu_{\rm SIM}$, we imposed a constraint

$$|\rho_{hh'}|^2 \;\geq\; 0.9. \tag{11}$$

in the numerical study.

Since the hidden-pion is stable and interacts with SM particles weakly, this particle can be the dark matter. We calculate the relic density and spin-independent DM-nucleon scattering cross section of the hidden pion. In the numerical study, we used micrOMEGAs. Because the lightest baryonic states can also be a stable dark matter, we have imposed only an upper bound of 2-sigma upper limit of the observed relic density

$$\Omega_{{\rm DM}=\pi_h} h^2 \lesssim 0.14. \tag{12}$$

In Fig. 3, we plotted the allowed region of the model. The colored region is allowed by both (11) and

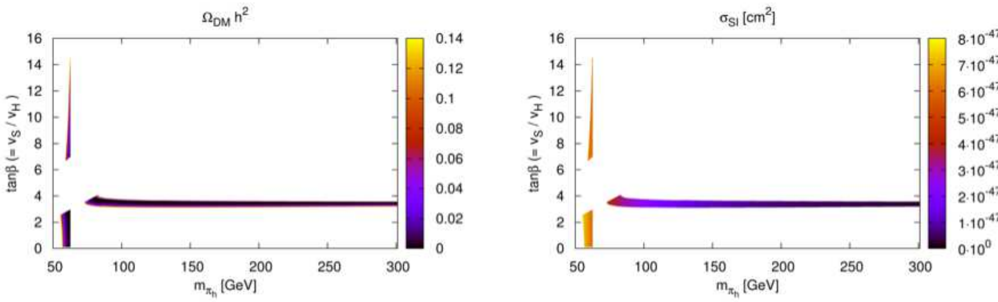

FIG. 3: Relic density and DM-nucleon cross section. [Left] Relic density of the hidden pion as cold dark matter [Right] the spin-independent DM-nucleon cross sections of the hidden-pion as cold dark matter.

(12). The allowed parameter space consists of three disconnected regions: (a) $m_{\pi_h} \sim 60$GeV and $\tan\beta \gtrsim 6$ (b) $m_{\pi_h} \sim 60$GeV and $\tan\beta \lesssim 4$ (c) $\tan\beta \sim 4$ and $m_{\pi_h} \gtrsim 70$GeV. A parameter region $m_{\pi_h} \sim 70$GeV and $\tan\beta \sim 5$ is forbidden since (11) cannot be satisfied.

We also plotted the spin-independent nucleon-DM cross section (Fig. 3, right). We found that the cross section can be small sufficiently and can easily evade the experimental limit of direct detection experiments[6].

We have also measured the mass of the non-SM scalar particle h_1 in Fig.4. In regions (a) and (b) the annihilation cross section of the DM is enhanced through the m_H resonance since $m_H \sim 2m_{\pi_h}$, whereas in (c) annihilation cross section is raised due to the h_1 resonance.

IV. SUMMARY

A scale-invariant extension of the SM with a singlet scalar and hidden-QCD sector is studied. We reformulated the hidden-QCD sector in terms of the linear-sigma model. A further study will be presented in an another paper[1].

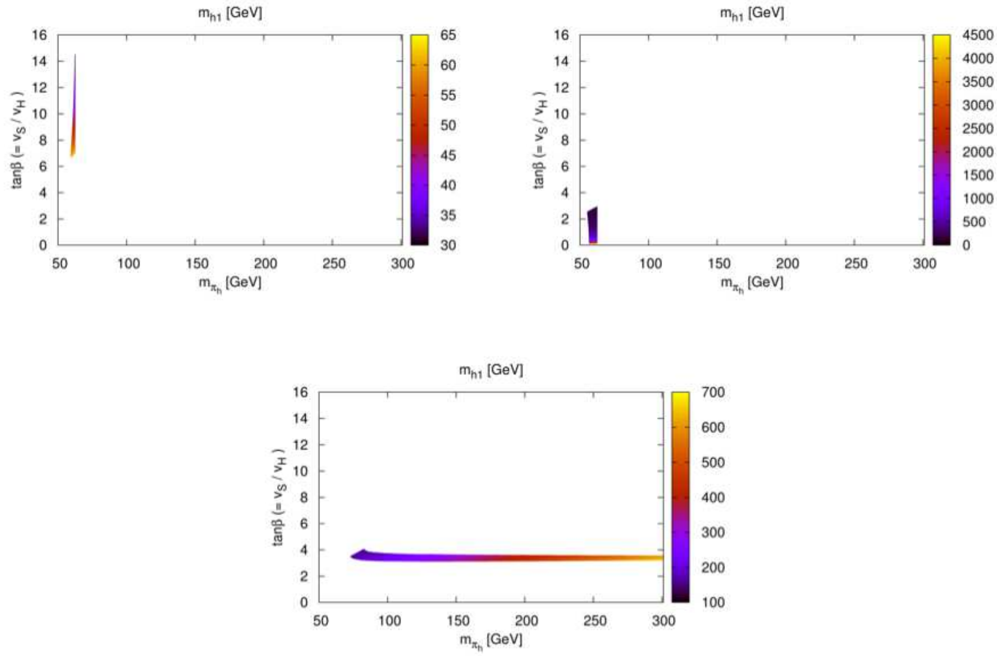

FIG. 4: Masses of the scalar h_1 ($m_{h_1} \neq 125$GeV) for three allowed regions. (upper left) $m_\pi \sim m_H/2$ and $\tan\beta \gtrsim 7$. (lower) $m_\pi \sim m_H/2$ and $\tan\beta \lesssim 4$, (upper right) $m_{h_1} \simeq 2m_{\pi_h}$.

Acknowledgments

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